Deflected Mirage Mediation : A Framework for Generalized SUSY Breaking

arXiv:0804.0592, arXiv:0806.2330 and phenomenology work in progress with L. Everett, P. Ouyang and K. Zurek

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Outline

Introduction

- Discovery of SUSY can connect low energy physics to high energy/Planck-scale physics. Low energy spectrum of superparticles depends on the mechanisms of $\cancel{\text{SUSY}}$ mediation.
- In local supersymmetry (SUGRA), M_{planck} suppressed nonrenormalizable operators can mediate $\cancel{\text{SUSY}}$ to the observable sector.

  $\rightarrow$ **Gravity/Moduli mediation**

$$m_{\text{soft}}^{(\text{grav})} = \frac{F}{M_{\text{planck}}} \sim m_{3/2}$$

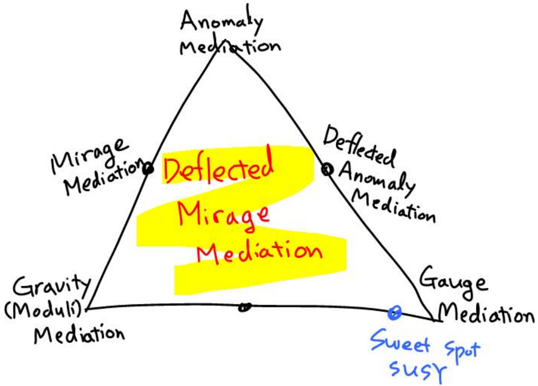
- $\cancel{\text{SUSY}}$ have been guided by solving the low energy problem, especially related to dangerous flavor violation from UV sensitive dynamics.

  $\rightarrow$ **Anomaly mediation**, **Gauge Mediation**

$$\begin{aligned} m_{\text{soft}}^{(\text{anom})} &= \frac{g^2}{16\pi^2} m_{3/2} \\ m_{\text{soft}}^{(\text{gauge})} &= \frac{g^2}{16\pi^2} \frac{F}{M_{\text{mess}}}, \text{ and } m_{3/2} \simeq \frac{F}{M_P} \ll m_{\text{soft}}^{(\text{gauge})}. \end{aligned}$$

- Until recently, Gravity/Moduli mediation, Anomaly mediation, and Gauge mediation are regarded as seperate scenarios since origins of $\not{SUSY}$ mechanism are different and the scales they set up are completely different.
- Recent lesson : Moduli Stabilization tends to make those mechanism come together.

  $\rightarrow$ **Mixed Anomaly-Modulus mediation** a.k.a *mirage mediation*
- Here, we propose a theoretical setup called **Deflected Mirage Mediation** where anomaly mediation, gauge mediation, gravity mediation contribute to the MSSM soft masses in similar size naturally. Although they have different origins, after stabilization, contribution to soft masses from each mechanism tend to be simiar.
- Relative ratios of each contribution in soft masses shows the information of stabilization.



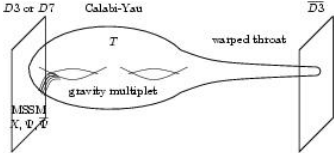
- This scenario gives a good parameterization of ~~SUSY~~ . Some of parameter limits reproduce the results of pure anomaly mediation, gauge mediation, and gravity mediation and mirage mediation. We can explore various conventional ~~SUSY~~ scenarios by dialing a small number of continuous parameters.

Mirage Mediation

Choi,Falkowski,Nilles,Olechowski,Porkoski(2004), Choi,Falkowski,Nilles,Olechowski (2005),

Choi, Jeong,Okumura (2005), Endo, Yamaguchi, Yoshioka (2005)

- KKLT Setup : Kachru-Kallosh-Linde-Trivedi(2003)



  - Superpotential : Flux + Nonperturbative

$$W = w_0 - Ae^{-aT}$$

$\longrightarrow$ stabilizes T moduli to SUSY AdS vacuum

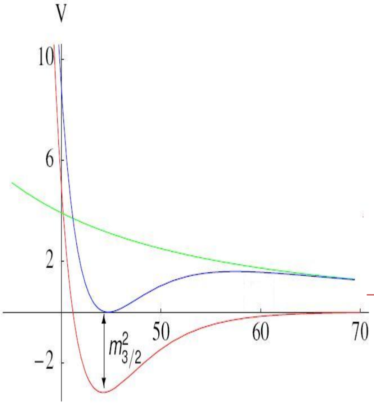
$$m_{3/2} = \frac{w_0}{(2T)^{3/2}}$$

$\longrightarrow$ EW scale $\cancel{\text{SUSY}}$ requires $w_0 \sim 10^{-15} \rightarrow aT \sim \log(M_{\rm pl}/m_{3/2})$

- moduli mass : $m_T \gg m_{3/2}$

$$(m_T)^2 \sim \frac{\partial^2 W}{\partial T^2} \sim (aT)^2 m_{3/2}^2$$

- Anti D-brane : source for ~~SUSY~~ (nonlinearly realized SUSY with warped scale.)



  - Dominant ~~SUSY~~ : Uplifting scalar potential

$$V \sim \frac{c e^{4A} M_{\rm st}^4}{(T+T^\dagger)^{2+n}} \qquad \text{n=0 for KKLT}$$

$\longleftarrow$ To cancel the cosmological constant

$$\Delta V \sim m_{3/2}^2$$

$\longrightarrow$ shifts stabilized T-value slightly. ΔT inversely proportional to m_T.

$$\frac{F^T}{T+T^\dagger} \sim \frac{1}{aT} m_{3/2} \sim \frac{1}{\log(M_{\rm pl}/m_{3/2})} \frac{F^C}{C}$$

- Anomaly mediation and moduli mediation are comparable numerically.

Matter Moduli Stabilization and Gauge mediation

- Once anomaly mediation is one of the dominant component, it tends to give similar size of contribution to other sources.

  $\longrightarrow$ easily gets **gauge mediation contribution**

- In most string compactifications,

1. Vector-like pairs $(\Psi, \overline{\Psi})$ charged under standard model gauge symmetry

2. Mass for such vector-like pairs obtained by another matter moduli X

$$W = X \Psi \overline{\Psi}$$

3. VEV of X is stabilized due to $\cancel{\text{SUSY}}$.

- **Supersymmetric Stabilization of X at a High scale**

  - **F term stabilization:** $W = \frac{1}{2} m_X (X - X_0)^2$

    $\longrightarrow$ Soft term (B-term) due to anomaly mediation $\sim m_{3/2} m_X (X - X_0)^2$. If $m_X \gg m_{3/2}$, the vacuum is not shifted and no additional ~~SUSY~~ .

  - **D term stabilization:** FI term (gauged $U(1)_R$ or anomalous $U(1)$)

    $\longrightarrow$ $U(1)_A$ breaking scale is $\mathcal{O}\left(\frac{1}{8\pi^2} M_{\rm st}\right) \gg m_{3/2}$. Green-Schwarz mechanism.

    $\longrightarrow$ Moduli-dependent FI term. Shift in $\langle T \rangle$ induces ~~SUSY~~ to F^X. However,

Choi, Jeong (2006)

$$\frac{F^X}{X} = \mathcal{O}\left(\frac{F^T}{T + \overline{T}}\right)$$

$\Rightarrow$ No additional ~~SUSY~~ contribution to MSSM $\rightarrow$ Mirage mediation.

X stabilization by SUSY breaking

F terms of X is given (roughly) by

$$\begin{aligned} F^X &= -e^{K/2} K^{X\bar{X}} D_{\bar{X}} W \\ &= \underbrace{-e^{K/2} K^{X\bar{X}} \partial_{\bar{X}} W}_{(A)} \quad \underbrace{-e^{K/2} K^{X\bar{X}} K_{\bar{X}} W}_{(B)} \end{aligned}$$

- **Radiative stabilization:** X is stabilized purely by $\cancel{\text{SUSY}}$ terms.
  - $\longrightarrow$ Due to radiative corrections, the mass term for X can change the sign in RGE.
  - $\longrightarrow$ stabilized near the point. (**Coleman-Weinberg mechanism**)
  - $\longrightarrow$ $\partial_X W \ll K_{\bar{X}} W$. (A) term vanishes.
  - Since (B) $\approx -m_{3/2} X$,

$$\frac{F^X}{X} = -m_{3/2} + \mathcal{O}\left(\frac{1}{8\pi^2} m_{3/2}, \frac{F^T}{T + \overline{T}} \right).$$

- **Higher-order stabilization ;** In general, X is stabilized due to superpotential terms like

$$W = \frac{X^n}{\Lambda^{n-3}}$$

and ~~SUSY~~ soft masses, and then $\partial_X W \sim K_{\bar{X}} W$, (A) $\sim$ (B).

$$\frac{F^X}{X} \sim m_{3/2}$$

$\Rightarrow$ Due to $W = X\Psi\overline{\Psi}$, the standard model fields get gauge mediation contribution

$$\Delta M_{1/2} \sim \frac{\alpha}{4\pi}\frac{F^X}{X}$$
$$\Delta m_0^2 \sim \left(\frac{\alpha}{4\pi}\frac{F^X}{X}\right)^2$$

- More precisely, we need to consider the effect of the moduli T.

$$\mathcal{L} = \int d^4\theta G + \int d^2\theta W + \text{h.c.}$$

$$G = -3C\bar{C}e^{-K/3} = -pC\bar{C}(T+\bar{T}) + \frac{1}{(T+\bar{T})^{n_X-1}}C\bar{C}X\bar{X}$$

$$W = C^3 W_0(T) + C^3\frac{X^n}{\Lambda^{n-3}}$$

$\longrightarrow$ consider the mixing terms between C,T and X.

$$F^X = -G^{X\bar{C}}\partial_{\bar{C}}\overline{W} - G^{X\bar{T}}\partial_{\bar{T}}\overline{W} - G^{X\bar{X}}\partial_{\bar{X}}\overline{W}$$

- Keep only the leading order terms

$$V \sim \mathcal{O}(X^{2n-2}) + \mathcal{O}(m_{3/2}X^n) + \mathcal{O}(m_{3/2}^2 X^2)$$

We obtain

$$\frac{F^X}{X} = -\frac{2}{n-1}\frac{F^C}{C}$$

$\longrightarrow$ independent of T moduli. determined by the nature of the superpotential self-interaction of X.

- Reasonably $n \geq 3$ (Higher order terms), or $n < 0$ (nonperturbative terms), then

$$-m_{3/2} \leq \frac{F^X}{X} < 2m_{3/2}$$

- Ratios among anomaly mediation, moduli contribution and gauge mediation are determined by discrete parameters.

Soft terms in Deflected Mirage Mediation

- We parameterize $\cancel{\text{SUSY}}$ by $(m_0, \alpha_m, \alpha_g)$

$$
\begin{aligned}
\frac{F^T}{T+\bar{T}} &= m_0 \\
\frac{F^C}{C} &= m_{3/2} = \alpha_m \ln(m_P/m_{3/2}) m_0 \\
\frac{F^X}{X} &= \alpha_g \frac{F^C}{C}
\end{aligned}
$$

- We also have $\tan\beta$ and $M_{\text{mess}} \equiv \langle X \rangle$.
- discrete parameters
  - modular weights $n_{H_u}, n_{H_d}, n_Q, n_U, n_D, n_L, n_E$
  - number of messenger pairs N (assuming they are SU(5) $\mathbf{5}, \bar{\mathbf{5}}$)
- This parameterization generally describe $\cancel{\text{SUSY}}$ of anomaly, gauge, and gravity mediation.

- Note that this scenario has two threshold scale : $M_{\rm GUT}$ and $M_{\rm mess}$
- Using the analytic continuation of wavefunction renormalization and gauge kinetic function into superspace with $\cancel{\text{SUSY}}$ fields C, X and T, we obtain MSSM soft masses.
- Gaugino mass :

$$\begin{aligned} M_a(M_{\rm GUT}) &= \frac{F^T}{T+\overline{T}} + \frac{\alpha_{\rm GUT}}{4\pi} b'_a \frac{F^C}{C} \\ \Delta M_a(M_{\rm mess}) &= -N\frac{\alpha_a(M_{\rm mess})}{4\pi}\left(\frac{F^C}{C}+\frac{F^X}{X}\right). \end{aligned}$$

- Trilinear scalar couplings:

$$\begin{aligned} A_{ijk} &= A_i + A_j + A_k, \\ A_i(M_{\rm GUT}) &= (p-n_i)\frac{F^T}{T+\overline{T}} - \frac{\gamma_i}{16\pi^2}\frac{F^C}{C}. \\ \Delta A_i(M_{\rm mess}) &= 0 \end{aligned}$$

- Soft scalar mass-squared parameters:

$$
\begin{aligned}
m_i^2(M_{\rm GUT}) &= (p/3 - n_i)\left|\frac{F^T}{T+\overline{T}}\right|^2 \\
&\quad - \frac{\theta_i'}{32\pi^2}\left(\frac{F^T}{T+\overline{T}}\frac{F^{\overline{C}}}{\overline{C}} + h.c.\right) - \frac{\dot{\gamma}_i'}{(16\pi^2)^2}\left|\frac{F^C}{C}\right|^2 \\
\Delta m_i^2(M_{\rm mess}) &= \sum_a 2c_a N \frac{\alpha_a^2(M_{\rm mess})}{16\pi^2}\left|\frac{F^X}{X} + \frac{F^C}{C}\right|^2
\end{aligned}
$$

where

$$
\begin{aligned}
\dot{\gamma}_i &= 2\sum_a g_a^4 b_a c_a(\Phi_i) - \sum_{lm} |y_{ilm}|^2 b_{y_{ilm}} \\
\theta_i &= 4\sum_a g_a^2 c_a(\Phi_i) - \sum_{lm} |y_{ilm}|^2 (p - n_i - n_l - n_m)
\end{aligned}
$$

$$
\begin{aligned}
M_a(M_{\rm GUT}) &= m_0\left[1+\frac{g_0^2}{16\pi^2}b'_a\alpha_m\ln\frac{M_P}{m_{3/2}}\right],\\
\Delta M_a &= -m_0 N\frac{g_a^2(M_{\rm mess})}{16\pi^2}\alpha_m\left(1+\alpha_g\right)\ln\frac{M_P}{m_{3/2}}.
\end{aligned}
$$

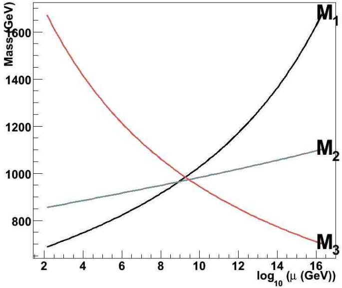
$$
\begin{aligned}
A_i(M_{\rm GUT}) &= m_0\left[(1-n_i)-\frac{\gamma_i}{16\pi^2}\alpha_m\ln\frac{M_P}{m_{3/2}}\right],\\
\Delta A_i &= 0.
\end{aligned}
$$

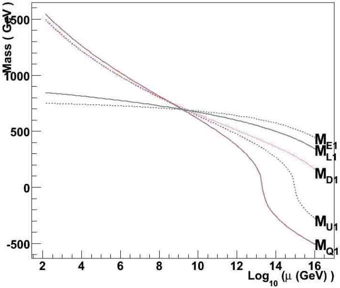
$$
\begin{aligned}
m_i^2(M_{\rm G}) &= m_0^2\left[(1-n_i)-\frac{\theta'_i}{16\pi^2}\alpha_m\ln\frac{M_P}{m_{3/2}}-\frac{\dot{\gamma}'_i}{(16\pi^2)^2}\left(\alpha_m\ln\frac{M_P}{m_{3/2}}\right)^2\right]\\
\Delta m_i^2 &= m_0^2\sum_a 2c_aN\frac{g_a^4(M_{\rm mess})}{(16\pi^2)^2}\left[\alpha_m(1+\alpha_g)\ln\frac{M_P}{m_{3/2}}\right]^2.
\end{aligned}
$$

Patterns of Soft masses in Deflected Mirage Mediation

- Mirage mediation has a peculiar mirage unification behavior of soft masses.

Choi, Jeong, Okumura (2005)

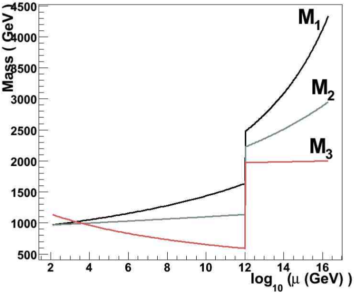


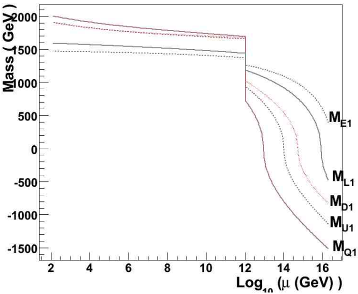


- Mirage scale :

$$M_{\rm mirage} \quad = \quad M_{\rm GUT}\left(\frac{m_{3/2}}{M_P}\right)^{\alpha_{\rm m}/2}$$

- Deflected mirage mediation significantly changes the mirage pattern.





- Deflected mirage scale for gaugino :

$$
\begin{aligned}
M_{\rm mirage} &= M_{\rm GUT}\left(\frac{m_{3/2}}{M_P}\right)^{\alpha_{\rm m}\rho/2} \\
\rho &= \frac{1+\frac{2Ng_0^2}{16\pi^2}\ln\frac{M_{\rm GUT}}{M_{\rm mess}}}{1-\frac{\alpha_{\rm m}\alpha_{\rm g}Ng_0^2}{16\pi^2}\ln\frac{M_P}{m_{3/2}}}
\end{aligned}
$$

- Gaugino mass can be unified at very low scale. General gaugino mass for $\cancel{SUSY}$ model was discussed in **"Gaugino code"** by Choi and Nilles (2007).
  - Light gluino (can be even lightest) $\rightarrow$ long-lived gluino
  - Sizable mixing between Bino and Wino $\rightarrow$ Well-tempered neutralino
  - Relatively less severe fine-tuning due to light gluino, negative stop mass square and large A-term. Dermisek-H.D.Kim (2006)

- $\mu/B\mu$ problem : Gravity mediation is comparable. So we can basically use Giudice-Masiero mechanism for μ. But B term is generically $\mathcal{O}(m_{3/2})$, so fine-tuning is needed.
  Using $U(1)_{PQ}$, **axionic mirage mediation** addressing $\mu/B\mu$ problem and cosmological moduli/gravitino problem has also been suggested recently.

Nakamura, Okumura, Yamaguchi: 0803.3725

$\mu/B\mu$ problem resolution using $U(1)_{PQ}$

Nakamura, Okumura, Yamaguchi: 0803.3725

$$\int d^4\theta C\overline{C}\left(H_u\overline{H_u} + H_d\overline{H_d}\right) + \left\{\int d^2\theta \mu C^3 H_u H_d + \text{h.c.}\right\}.$$

- $\mu/B\mu$ problem : When **Anomaly mediation** dominates,

$$B \sim \frac{F^C}{C} \sim \mathcal{O}(m_{3/2})$$

- Must forbid tree-level mass term : PQ symmetry.
- Use matter moduli X as a PQ symmetry breaking field.
- Leading $B\mu$ terms are canceled between anomaly mediation and gauge mediation.
- Subleading term is $\sim \frac{F^T}{T+\overline{T}}$ and $\sim \frac{1}{16\pi^2}\frac{F^C}{C}$.

- model:

	H_u	H_d	X	Y	T
PQ Charge	-2	-2	-2	-2	4

$$\begin{aligned} W &= y_1 T H_u H_d + y_2 XYT \\ -3\exp(-K/3) &= |X|^2 + |Y|^2 + |T|^2 + \kappa \overline{X} Y + \text{h.c.} \end{aligned}$$

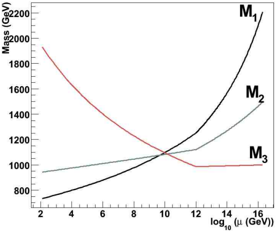
- Stabilize X by Coleman-Weinberg mechanism. $\rightarrow \langle X \rangle$ at intermediate scale.
- Y and T get massive. Integrate out T

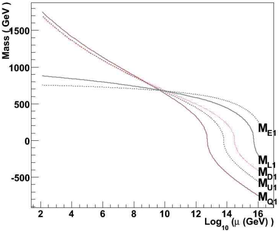
$$Y \approx -\frac{y_1}{y_2}\frac{H_u H_d}{X}$$

- Then, generate μ term and B term $\sim \left(\frac{F^C}{C} + \frac{F^X}{X}\right)$.

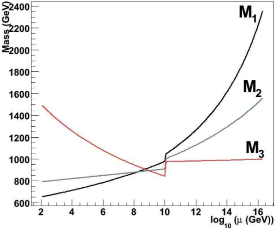
$$\Delta\mathcal{L} = -\kappa \frac{y_1}{y_2}\int d^4\theta \, \frac{\overline{CX}}{CX}(CH_u)(CH_d) + \text{h.c.}$$

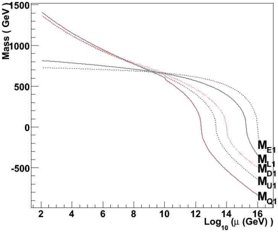
- Coleman-Weinberg stabilization case : $W(X) = 0$



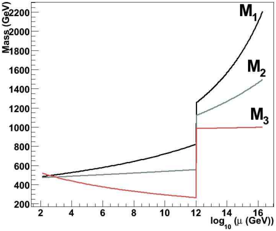


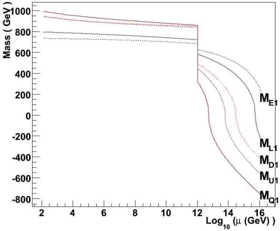
- Stabilization by nonrenormalizable op : $W(X) = \frac{X^4}{M_{\rm pl}}$



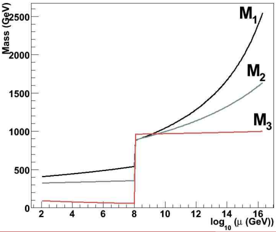


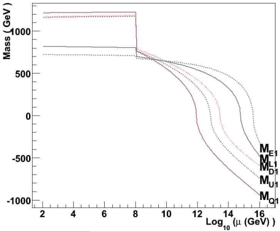
- Stabilization by nonperturbative potential :
$W(X) = \frac{\Lambda^4}{X}, \Lambda \sim 10^{10}$ GeV



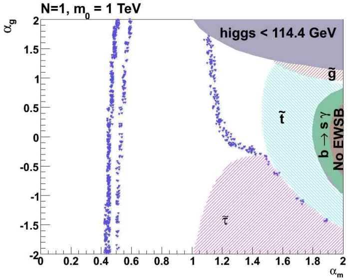


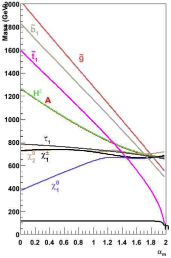
- Stabilization by nonperturbative potential :
$W(X) = \frac{\Lambda^4}{X}, \Lambda \sim 10^{7}$ GeV

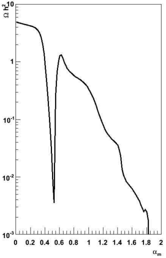


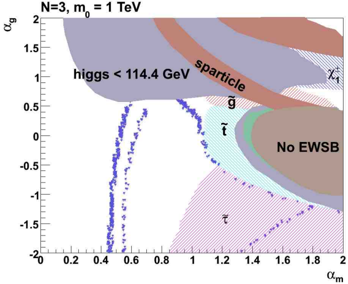


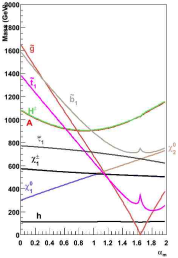
- Parameter Scan with thermal neutralino dark matter relic density

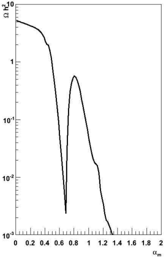












Conclusion

- General consideration of moduli stabilization lead us to unexplored $\cancel{\text{SUSY}}$ parameter space.
- Deflected mirage mediation setup provides a generalized framework for regarding the relative effect of well-known conventional $\cancel{\text{SUSY}}$ scenarios : Anomaly mediation, Gauge Mediation and Gravity Mediation.
- Using PQ symmetry, μ term and $B\mu$ term can be suppressed than $m_{3/2}$ due to cancellation between gauge mediation and anomaly mediation.
- Relatively light colored particles and less fine-tuned regions are more plausible in this scenario.
- Thermal dark matter relic density is well explained with Bino/Wino mixed or Bino/Wino/Higgsino mixed neutralino LSP in this scenario.
- Phenomenology and benchmark study are now being done.